Bubble Point Measurements With Liquid Methane of a Screen Channel Capillary Liquid Acquisition Device

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Abstract

Liquid acquisition devices (LADs) can be utilized within a propellant tank in space to deliver single-phase liquid to the engine in low gravity. One type of liquid acquisition device is a screened gallery whereby a fine mesh screen acts as a "bubble filter" and prevents the gas bubbles from passing through until a crucial pressure differential condition across the screen, called the bubble point, is reached. This paper presents data for LAD bubble point data in liquid methane (LCH_4) for stainless steel Dutch twill screens with mesh sizes of 325 by 2300. These tests represent the first known nonproprietary effort to collect bubble point data for LCH_4.

Introduction

Multiple propellant management devices (PMD) can be utilized within the propellant tank in space to deliver single-phase fluid to the engine in low gravity. Varying acceleration and gravity regimes will probably lead to a system design using multiple varieties of PMDs. One type of PMD, a liquid acquisition device (LAD) uses capillary flow and surface tension to acquire liquid.

Capillary flows LADs have been well characterized for storable propellants (Ref. 1). In recent years, on-going research has evaluated LADs in liquid oxygen (LO_2), liquid nitrogen (LN_2) and liquid hydrogen (LH_2). NASA has determined that liquid methane (LCH_4) is also a promising propellant option for future exploration missions. Understanding LCH_4 characteristics and how it performs in cryogenic fluid systems (including LADs) is critical to advancing technology that would utilize LCH_4 as a propellant.

A number of screen weaves are suitable for use in LADs. The weave pattern, which refers to the over/under pattern used in manufacturing the screen, is an important parameter affecting the choice of screen; certain weaves of wires produce much finer pore sizes than other weaves. The tightness of the weave (mesh) and the weave pattern determine the geometry of the pores in the screen. A given mesh screen is designated by two numbers; the first number refers to the number of shute wires and the second number refers to the number of warp wires. In a Dutch twill screen, each shute wire travels over two warp wires before going under a warp wire. Figure 1 provides detail on the Dutch twill weave pattern. Figure 2 shows a scanning electron microscope (SEM) photograph of a 325 by 2300 mesh Dutch twill screen.
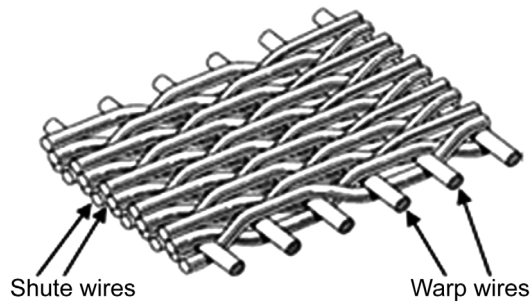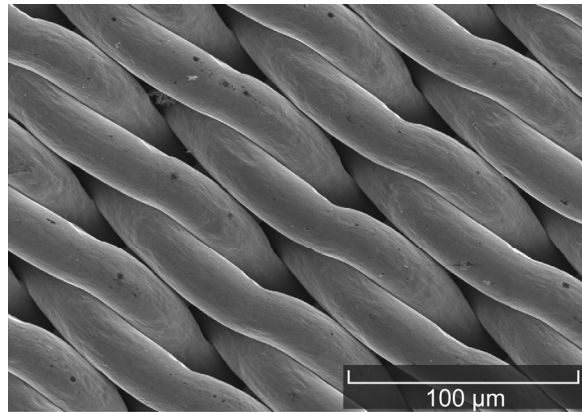
Figure 1.—Dutch twill weave LAD screen.

Figure 2.—Scanning Electron Microscope (SEM) photo of a 325 by 2300 mesh screen sample.

The geometry of the pore and the fluid surface tension determine the bubble point of the screen. "Bubble Point" is defined as the differential pressure across the screen that overcomes the surface tension of the liquid on the screen. A high bubble point (fine screen mesh) is desirable to ensure single phase (liquid) fluid delivery and good wicking of fluid into the screen pores. Fine mesh screens, however, tend to generate a large pressure loss during outflow through the screen. The total pressure loss in the system must be less than the bubble point pressure to prevent vapor ingestion into a LAD channel.

NASA Glenn Research Center has an on-going test program to develop data for LAD performance for a variety of cryogenic propellants (Refs. 2 to 4). This paper presents new bubble point data in LCH$_4$ for stainless steel Dutch Twill Screens with a mesh size of 325 by 2300. Testing was conducted in 2006 and 2007 at Glenn Research Center's Creek Road Complex in the Cryogenic Components Lab 7 (CCL-7). It is a small scale cryogenic fuel test stand designed for component screening (Ref. 5).

Nomenclature

Ca   Capillary number $= \left(\dfrac{\mu U}{\sigma} \right)$

D_P Effective pore diameter of the screen weave
D_H Hydraulic diameter
NBP   Normal Boiling Point
ΔP_{BP} Bubble Point pressure
r Bubble radius
U Bubble velocity

μ   Dynamic viscosity
ν   Kinematic viscosity
θ_c Contact angle of the liquid on the screen material
σ   Surface tension of the liquid

Liquid Methane Bubble Point Tests

Test Hardware Design

Figure 3 shows the cylindrical test article used for bubble point testing. A screen sample is welded into the flanged top of the test article. The flanged design allows for rapid change out of various screen samples. A mirror aids in viewing the screen surface. Positioning the mirror over the screen surface provides both a side view and top view from a single camera to allow observation of gas bubbles passing through the screen. Instrument taps on the test article connect to pressure transducers external to the dewar and measure differential pressure across the LAD screen as shown in Figure 4. The assembled test article is shown installed inside the dewar in Figure 5.

Screen Size

The LAD screen used for these tests is a 325 by 2300 mesh Dutch Twill screen. The screen is welded to the top flange of the test article shown in Figure 3. The screen itself has a diameter of 2.5 in. (6.25 cm) and a surface area exposed to the liquid of 4.91 in.^{2} (31.7 cm^2).

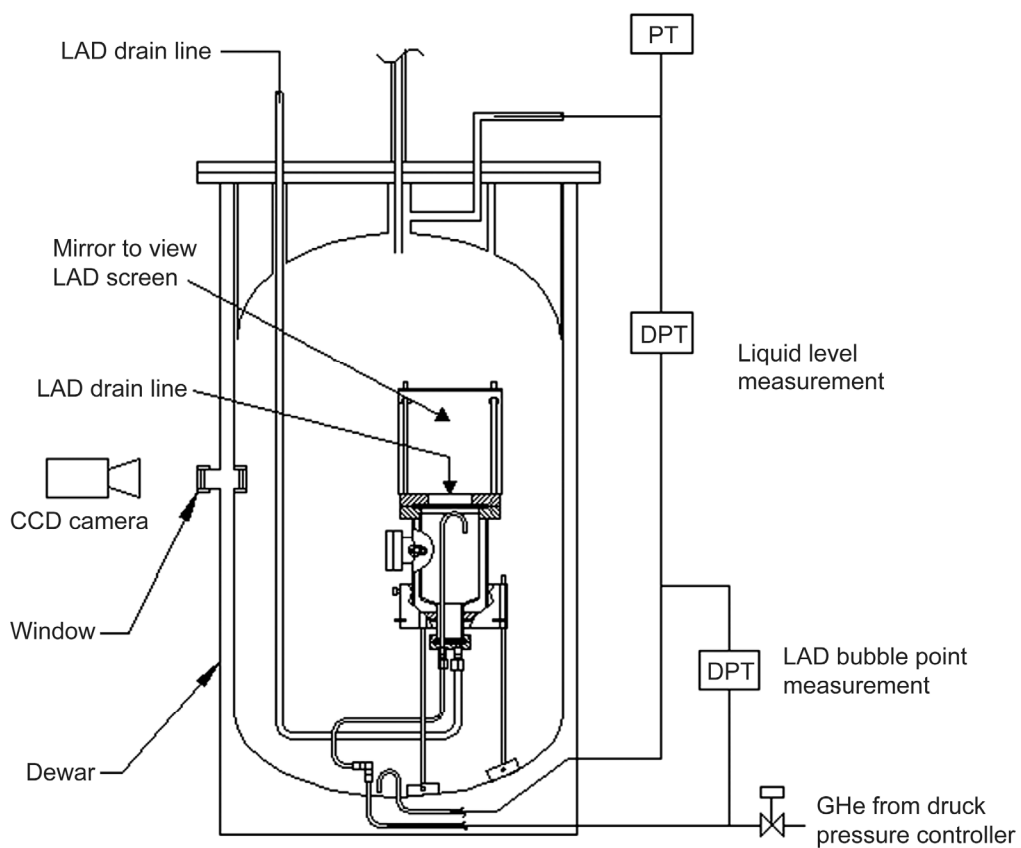Figure 3.—Test Article used for bubble point testing.

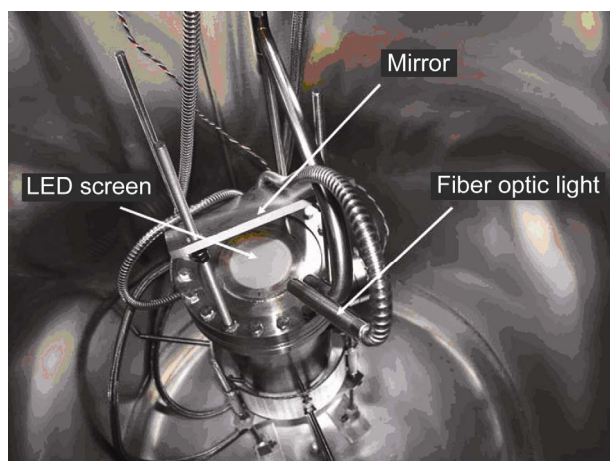Figure 4.—LAD test article shown inside dewar.

Figure 5.—Test article installed inside the cryogenic dewar.

Test Facility

CCL-7 is a small scale screening facility for concept and component testing. In addition to component screening, the facility can perform propellant transfer, propellant conditioning (warming and sub-cooling), and vent flow tests. CCL-7 safely handles 300 gal (1130 liter) of both LH_2 and LN_2, and 120 gal (450 liter) of LCH_4. Gaseous helium (GHe) and gaseous nitrogen (GN_2) are available on-site.

Tests can be performed in either a "Supply" or "Receiver" vacuum jacketed Dewar at the facility; although the Supply Dewar is generally used for propellant conditioning. The Supply Dewar is a vertical cylinder with a 22 in. (0.55 m) diameter and 54 in. (1.36 m) height. It has an 11 ft^3 (0.32 m^3) internal volume and an operating pressure of 40 psia (274 KPa). An instrument rake equipped with silicon diodes provides temperature measurements and liquid level indication. A simplified schematic of the CCL-7 test facility showing Supply and Receiver Dewars at CCL-7 is shown in Figure 6.

For this test program, the LAD hardware shown in Figure 4 was installed in the Receiver Dewar. Fluid supply and vent piping, and instrumentation lines pass through the lid of this Dewar. The diameter of the Receiver Dewar is 22 in. (0.55 m). An instrument rake equipped with silicon diodes provides temperature measurements and liquid level indication. The Receiver Dewar is 42 in. (1.07 m) deep, has an internal volume of 8.1 ft^3 (0.23 m^3), and has a working pressure of 25 psia (170 KPa). A window in the sidewall is located 22 in. (0.55 m) from the bottom of the dewar.

LCH_4 is transferred to the test facility through a 0.75 in. (20 mm) diameter vacuum jacketed hose and piping from a portable 450 liter liquid methane vacuum jacketed Dewar. The cryogen is transferred either into the Supply Dewar and from there to the Receiver Dewar, or directly into the Receiver Dewar. The Supply and Receiver Dewars can vent either directly to atmosphere or through a series of air ejectors. The ejectors allow the dewars to operate at a minimum pressure of approximately 2.5 psia (17 KPa). The Receiver Dewar vent valve is operated either open loop, or with a proportional—integral—derivative
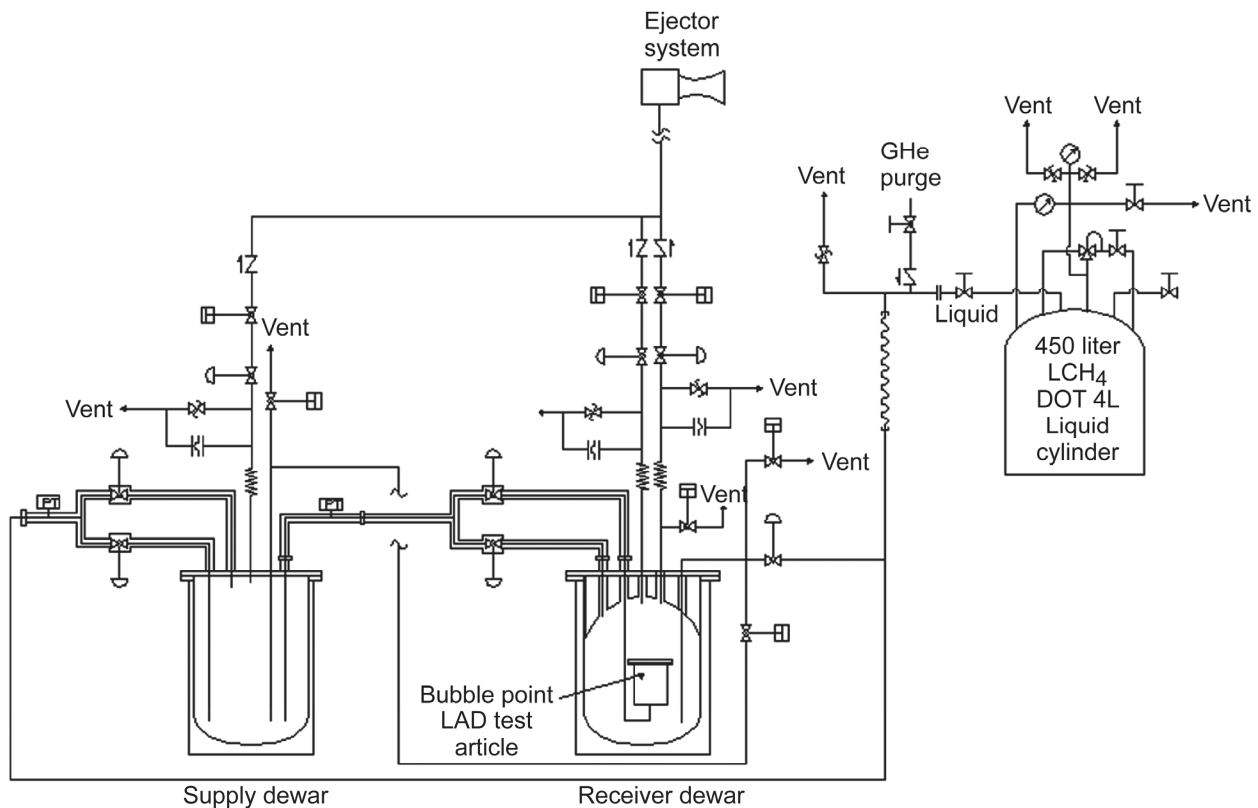

Figure 6.—Simplified test facility schematic diagram.

(PID) loop in the programmable logic controller (PLC) control system, and can control backpressure in the Receiver Dewar to within ±0.05 psi (±0.34 KPa). A separate vent line with an open loop proportional valve is available for test articles installed inside the Receiver Dewar. Gasses evolved during testing from the dewars and test articles can vent directly to atmosphere, or through a series of four mass flow meters. The LAD test article installed inside the Receiver tank has an independently controlled pressurization system. Figure 5 shows a simplified schematic of the LAD hardware installed in the Receiver Dewar.

Instrumentation/Data Acquisition

CCL-7 utilizes a LabView (National Instruments) based data collection system. Up to 320 channels of data can be collected at a nominal rate of 1 Hz. Many of the facility channels are pre-configured for standard instruments including thermocouples, pressure transducers, and silicon diodes. Interlocks, alarms and shutdowns protect the research hardware and the facility. Operator controlled open-loop processes are used to provide flexibility.

Video

It is necessary to observe the LAD screen during test to determine at what differential pressure bubbles break through the screen in order to determine the bubble point pressure. A CCD video camera located in the test facility views the LAD screen through the view port on the side of the Receiver Dewar. The video signal is transmitted to a monitor in the test facility control room, and is recorded on a VHS format video tape. The video data is time stamped and synchronized with the data collected to aid in post test data processing.

Test Objectives/Overview

The purpose of this experimental program was to determine bubble point characteristics of a 325 by 2300 mesh screen LAD by performing bubble point tests in LCH_4. A wealth of data exists for isopropyl alcohol (IPA) that can be correlated to storable propellants, but the database needs to be extended to cryogenic propellants. Bubble point data has been collected for LN_2, LO_2, and LH_2. This is the first known effort to collect LAD bubble point data for LCH_4. Data was collected for both normal boiling point (NBP) and sub-cooled LCH_4. Bubble point was determined by observing the LAD screen via a CCD video camera and correlating the observed bubble breakthrough with concurrently collected sensor data.

Initial check-out tests were performed at the facility using LN_2. Following those tests, LCH_4 was transported on site and connected to the test facility dewars. The LCH_4 was supplied in portable 450 liter dewars filled by an industrial gas supplier. Each shipment of LCH_4 was supplied with a chemical analysis. Details of the LCH_4 specification, supplier, and analysis of a typical delivery are given in Appendix A.

Test Procedure

LAD Screen Bubble Point Tests

For bubble point testing, the LAD test article was placed inside the Receiver Dewar as shown in Figure 5. A precision differential pressure controller was used to pressurize the LAD test article to determine bubble point. The pressure controller was referenced to the dewar ullage pressure. This allowed the controller to set the pressure inside the LAD test article from 0 to 50 in. H_2O (12.44 KPa) above ullage pressure. During fill, the pressure inside the LAD test article was set at approximately 30 in. H_2O (7.47 KPa) above dewar ullage pressure to prevent the test article from flooding. As the dewar filled and the entire screen surface became wetted, surface tension forces also helped to prevent flooding of the LAD test article. The dewar was filled with LCH_4 to approximately 8 in. (20 cm) above the top of the LAD screen. After the fill was complete, the pressure in the dewar was increased from atmospheric pressure to approximately 20 psia (138 KPa) to suppress any boiling of LCH_4. The pressure controller was then used to gradually ramp down the pressure inside the test article until gas bubbles were no longer

seen coming through the screen. This *reseal* pressure was noted, and the pressure decreased by several more inches H_2O. The pressure was then gradually increased inside the test article in 0.1 in. of water (0.28 KPa) increments until gas bubbles broke through the screen surface. This *bubble point* pressure was noted, and the pressurization/depressurization cycle repeated a number of times to obtain additional data. Pressure across the screen surface was measured using sensitive differential pressure transducers.

Fluid Conditioning

Tests were conducted with LCH_4 at two different fluid conditions. For the first series of tests, the Receiver Dewar was filled with LCH_4 from the portable liquid cylinder while the Receiver Dewar was vented to atmospheric pressure, essentially saturating the fluid at NBP conditions. The dewar was then pressurized with GHe for bubble point tests. A second series of tests was performed with subcooled liquid. For these tests, the LCH_4 was transferred to the Supply Dewar. The pressure in the Supply Dewar was reduced using the facility ejectors. This subcooled the LCH_4 to approximately 175 °R (97 K). The Supply Dewar was then pressurized with GHe, and the subcooled LCH_4 transferred to the Receiver Dewar for bubble point testing. The LCH_4 did absorb some heat during transfer, and final liquid temperatures were 186 to 188 °R (103 to 104 K) for subcooled tests.

Test Results/Observations

Eighteen tests were performed with warm LCH_4 saturated near NBP conditions (LCH_4 temperature 201 to 206 °R (112 to 114 K)). Twelve tests were performed using subcooled LCH_4 (temperature 186 to 188 °R (103 to 104 K)). Tests were performed at these two different fluid conditions to evaluate bubble point pressures at several values of surface tension.

Bubble point pressure is calculated using Equation (1) (Ref. 6)

$$\Delta P_{BP} = \frac{4\sigma \cos \theta_c}{D_p} \tag{1}$$

Here, σ is the surface tension of the liquid and θ_c is the contact angle of the liquid on the screen material. For LCH_4, $\theta_c \approx 0$ so $\cos \theta_c = 1$. The effective pore diameter of the screen weave is D_P. Note that the standard practice for determining the effective pore diameter for a particular screen is to measure ΔP_{BP} with a special bubble-point apparatus using IPA as a reference liquid and calculating D_P for the screen weave from Equation (1). This value of D_P was used to compute the bubble-point pressure for the 325 by 2300 screen weave and LCH_4. IPA bubble point tests were performed on the identical screen used for this test series (Ref. 7). The D_P based on that data was determined to be 0.000567 in. (0.0144 mm). Table 1 shows average values of predicted and measured bubble point pressures from tests.

TABLE 1.—LCH_4 MEASURED AND PREDICTED ΔP_{BP}

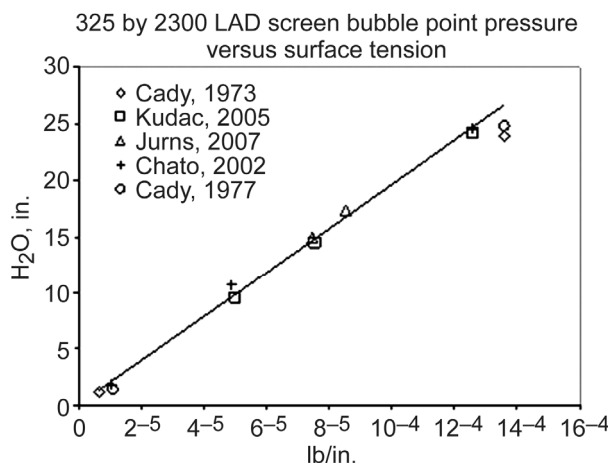| LCH_4 Temperature, (°R)	Surface tension, (lb/in.)	ΔP_{BP} Measured, (in. H_2O)	Std Dev., (in. H_2O)	ΔP_{BP} Predicted, (in. H_2O)	% error
204±2	7.463×10^{-5}	14.11	0.38	14.59	−3.3
187±1	8.525×10^{-5}	17.37	0.36	16.66	4.1

Figure 7.—Bubble point data and predictions for LO_2, LN_2, LCH_4, LH_2, and IPA.

Comparison With Historical Data

Bubble point data has previously been reported for IPA (Refs. 2, 4, 7, and 8), LH_2 (Refs. 2, 4, and 8), LN_2 (Refs. 2 and 7), and LO_2 (Ref. 7). Predicted values for bubble point pressure were calculated using Equation (1). Cady (Ref. 8) reported bubble point values for LH_2 based on liquid saturated at 50 psia (344.7 KPa). Kudlac (Ref. 7) reported bubble point predictions for LO_2 and LN_2 were based on saturated liquid at NBP. Chato (Ref. 2) did not report fluid conditions, but a review of data from the Chato tests indicated that LN_2 temperature was 142.5 °R (79.2 K), and LH_2 temperature was 39.6 °R (21.9 K). Using surface tension values for these conditions, predicted bubble point values were calculated using Equation (1). A plot of predicted and measure bubble points versus surface tension for a 325 by 2300 LAD screen is shown in Figure 7. The data are shown in tabular form in Table 2.

TABLE 2.—PREDICTED AND MEASURED BUBBLE POINT PRESSURES

Fluid	Surface tension, (lb/in.)	ΔP_{BP} measured, (in. H_2O)	ΔP_{BP} Predicted, (in. H_2O)	Source
LH_2	6.526E-06	1.216	1.285	Cady, 1973
IPA	1.359E-04	23.9	-------	Cady, 1973
LH_2	1.087E-05	1.44	2.14	Cady, 1977
IPA	1.359E-04	24.8	26.75	Cady, 1977
IPA	1.256E-04	24.54	24.73	Chato, 2002
LN_2	4.888E-05	10.67	9.62	Chato, 2002
LH_2	1.028E-05	1.83	2.02	Chato, 2002
LN_2	4.996E-05	9.6	10.7	Kudlac, 2005
LO_2	7.537E-05	14.5	14.11	Kudlac, 2005
IPA	1.256E-04	24.18	-------	Kudlac, 2005
NBP LCH_4	7.463E-05	14.11	14.59	Jurns, 2007
Subcooled LCH_4	8.524E-05	17.37	16.66	Jurns, 2007

Surface tension values for the current LCH_4 tests were obtained from the NIST thermodynamic fluid property software program GASPAK (Ref. 9). The source in this program for surface tension properties is Sprow & Prausnitz (Ref. 10). In the course of analyzing data from the LCH_4 tests, surface tension values as defined by Fuks & Bellemans (Ref. 11) were also considered. A comparison of these two sources indicates that the Fuks & Bellemans values for surface tension were approximately 3 to 4 percent lower than the Sprow & Prausnitz values. From Equation (1), it is apparent that the predicted values for bubble point pressure would be correspondingly 3 to 4 percent lower.
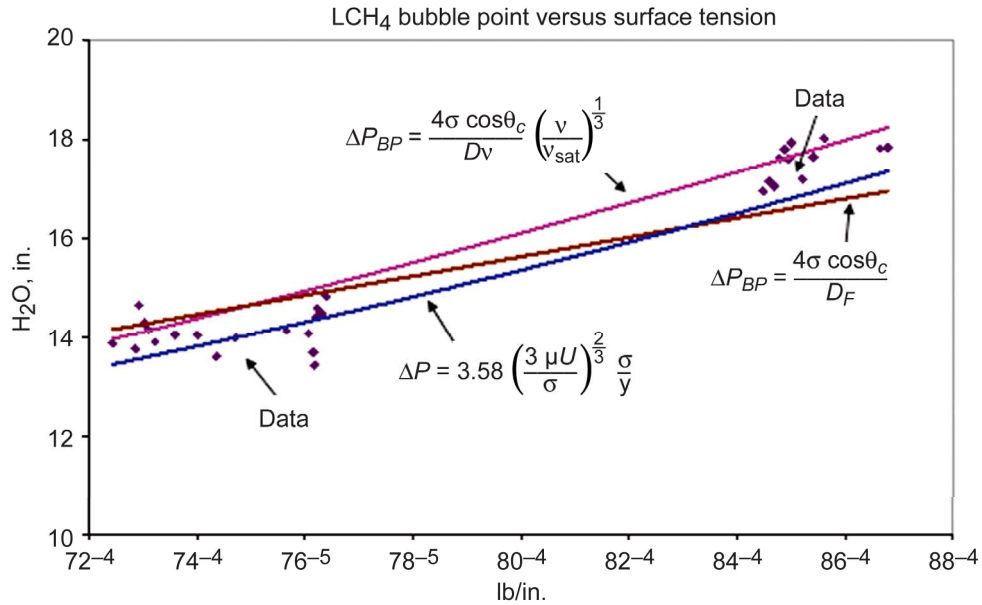
Figure 8.—LCH$_4$ bubble point data and predictions based on Equations (1), (2), and (3).

LCH$_4$ ΔP_{BP} Predictions Based on Surface Tension

Equation (1) predicts bubble point reasonably well for NBP liquid. However, as can be seen for the LCH$_4$ test data summarized in Figure 8, it under-predicts bubble point pressure for subcooled liquid. Although Equation (1) calculates bubble point only as a function of screen pore diameter and surface tension, both Kudlac (Ref. 7) and Dodge (Ref. 6) state that bubble point is also influenced by liquid viscosity and density. However, neither of these terms is included in Equation (1).

In an attempt to improve the correlation for bubble point, we considered other treatments of pressure drop of a bubble through a screen. The bubble point is the maximum pressure that surface tension forces can prevent a gas bubble from flowing through the screen or, viewed differently, the pressure difference at which gas flow through the screen is initiated.

Bretherton (Ref. 12) related the pressure drop for a long bubble through a tube as

$$\Delta P = 3.58 \left(\frac{3\mu U}{\sigma} \right)^{2/3} \frac{\sigma}{r} \tag{2}$$

Where U is the bubble velocity, albeit very slow. The value inside the parenthesis of Equation (2) is three times the Capillary Number (Ca). Gauglitz and Radke (Ref. 13) used a similar relationship for bubble traversing through constricted capillaries, similar to those found in porous media. If we view LAD screens as thin porous media and utilize this relationship to evaluate bubble point measurements considering liquid viscosity and surface tension, the result correlates well with data. This is plotted in Figure 8. Note that we did not measure the bubble velocity, but determined it from Equation (2). We note that rather than using the Capillary number (and hence the viscosity) raised to the 2/3 power, if we consider the Kudlac (Ref. 7) and Dodge (Ref. 6) statement that bubble point is also influenced by liquid viscosity and density, and multiply Equation (1) by a normalized kinematic viscosity raised to the 1/3 power as shown in Equation (3), we achieve similarly good results. The advantage of Equation (3) is that it provides good correlation with the data without having to consider bubble velocity U. Resolution of this behavior is ongoing.

$$\Delta P_{BP} = \frac{4\sigma\cos\theta_c}{D_p}\left(\frac{\nu}{\nu_{NBP}}\right)^{\frac{1}{3}} \tag{3}$$

LAD Screen Characteristics

Data presented is from different tests with different screens. Cady tests from the 1970's report for 325 by 2300 mesh screens with warp and shute wire diameters of 0.0015 and 0.001 in. (0.038 and 0.024 mm) respectively. Cady reports pore diameter = 0.00039 in. (0.0099 mm) absolute, 0.00047 to 0.00049 in. (0.0119 to 0.0124 mm) experimental equivalent pore diameter, where the absolute pore diameter is given by the manufacturer, and the experimental equivalent pore diameter is calculated using Equation (1). Manufacturers' data from 325 by 2300 screen mesh LAD screens used for NASA GRC tests list the warp and shute wire diameters as 0.0014 and 0.0011 in. (0.0355 and 0.0279 mm) respectively. Kudlac does not report D_P, but it was calculated to be 0.000567 in. (0.0144 mm) based on IPA tests and Equation (1). This same value of D_P was used in this report. SEM images were taken of the screen used for the LCH$_4$ tests as shown in Figure 2. Scaled measurements from these photographs indicated warp and shute wire diameters of 0.00165 and 0.00098 in. (0.0419 and 0.0249 mm) respectively. Of course, the SEM photograph is only calculated for one small area and cannot be construed as accurate for the entire screen, considering variations in the manufacturing and fabrication of the screen. However, it does corroborate the manufacturers' data.

In an effort to understand the relationship between D_P and the physical characteristics of the LAD screen, we examined screen geometry configuration to see if they can be utilized to predict the measured bubble points associated with these screens. The analysis was based on the physical dimensions of the openings or gaps through the screen and the fact that gas phase must constrict to a certain size in order to be able to enter the hole. Three types of holes or gaps were considered: (1) Projections into the top surface of the screen, (2) gaps between two adjacent shute wires at the warp wire and (3) gaps among four adjacent shute wires. Method (1) yields an equivalent diameter of 0.00065 in. (0.0165 mm). Method (2) yields an equivalent diameter of 0.0003 in. (0.0076 mm). Method (3) yields an equivalent diameter of 0.0004 in. (0.0102 mm). Note that method (3) yields a similar value as the 0.00039 in. absolute pore diameter reported by Cady. Details of this analysis are given in Appendix B.

It is apparent that there are variations in screen dimensions between manufacturers and between different batches from the same manufacturer. Although values for D_P may be inferred from the physical dimensions, the standard method of calculating D_P using Equation (1) and IPA should be used with the specific screen under consideration when designing LADs.

Conclusions

We have shown in this series of LAD tests that LCH$_4$ bubble point data is repeatable and consistent with pre-test predictions for NBP liquid. We also note that Equation (1) appears to under-predict ΔP_{BP} for subcooled LCH$_4$. The prediction may be improved by including a kinematic viscosity term as per Equation (3). However, this needs to be evaluated with other cryogenic fluids. Future work may include reanalyzing existing data for LO$_2$, LN$_2$, and LH$_2$ to include this factor. We have investigated the geometry of LAD screens, and agree that screen design parameters should be determined experimentally when designing a LAD for a specific application. LCH$_4$ joins the list of cryogenic fluids that have been characterized with LAD screen channel devices to show that they can consistently deliver single phase cryogenic fluid with system pressure losses less than bubble point pressure for the fluid/screen combination.

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Appendix A—Liquid Methane Supply

Specifications and Supplier

At the onset of this test program, there was no agreed upon LCH_4 purity specification. Liquefied natural gas (LNG) consists largely of LCH_4, with a number of other hydrocarbon constituents and impurities. Although LNG is widely available throughout the world, NASA had determined that it would be unsuitable for use as a propellant due to variations in properties making predictions of accurate performance impossible. NASA worked with several suppliers to determine what higher purity sources of LCH_4 were available, and to what specification it could be produced and delivered. The LCH_4 supplier worked with NASA to develop the purity specification shown in Table 3. The last column shows the analysis of a typical delivery of LCH_4.

TABLE 3.—LCH_4 PURITY SPECIFICATION FROM AIRGAS

Impurity	Specification	Typical Delivery
Methane	99.9%	99.9%
Oxygen	<2 ppm	<1 ppm
Nitrogen	<500 ppm	29 ppm
Total Atmospheric Gases	------------	<125 ppm
Ethane	<30 ppm	10 ppm
Carbon Monoxide	<1 ppm	<1 ppm
Carbon Dioxide	<50 ppm	<50 ppm
Propylene	<1 ppm	Other total
Ethylene	<1 ppm	hydrocarbons
Propane	<5 ppm	<1 ppm
Hydrogen	<1 ppm	
Sulfur	<0.5 ppm	<0.1 ppm
Moisture	<1 ppm	<0.05 ppm

Subsequent to the start of this test program, MIL SPEC MIL-PRF-32207 "Performance Specification Propellant Methane" was issued. This specification is shown in Table 4 for comparison. Note that the LCH_4 used for this test most closely matches Grade "C" product.

TABLE 4.—MIL-PRF-32207 PERFORMANCE SPECIFICATION PROPELLANT METHANE

Property	Grade		
	A	B	C
Purity (CH4), % volume, min	98.5	99.9	99.97
Water, ppm by volume, max	1	0.5	0.5
Oxygen, ppm by volume, max	1	1	1
Nitrogen, ppm by volume, max	5000	100	100
Carbon Dioxide, ppm by volume, max	125	50	50
Total atmospheric gases, ppm by volume, max (Ar, O_2, N_2, He, Ne)	5000	125	125
Ethane (C2H6), ppm by volume, max	5000	500	100
Propane (C3H8), ppm by volume, max	3000	500	100
Other hydrocarbons, ppm by volume, max	1	1	1
Total Sulfur, ppm by volume, max	1	0.1	0.1
Non-volatile residue, mg/L, max	10	1	1

LCH$_4$ Containers and Delivery

Product produced to this specification was delivered to the NASA Glenn Research Center in 450 liter portable cryogenic dewars. DOT restrictions limited filling of the containers to 360 liter of product. Product was produced near Toledo, Ohio and trucked to NASA Glenn in Cleveland.

Product Purity

Early on in the test program, we noticed some problems transferring liquid between test dewars. We suspected that this may be due to plugging of a filter located in the transfer line between the test dewars. The system was emptied and purged, and the filter was removed. The filter was then washed with a solvent, and the filtrate examined visually and using Energy Dispersive X-ray Spectroscopy (EDS). Visual examination of the filtrate indicated some small metallic particles, and the EDS analysis indicated presence of silicon, aluminum and iron (other elements were detected, but were discounted as being components of the filter paper). We also took SEM photographs of the 10 µ filter before and after it was cleaned with solvent. Figures 9 and 10 show the filter in the pre-cleaned and post-cleaned condition. After the filters were cleaned, the test system performed well with no further issues.
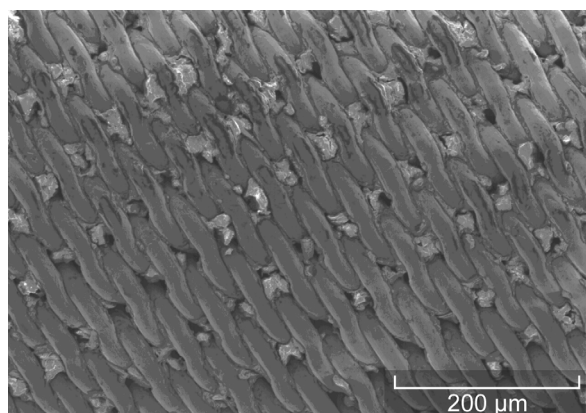

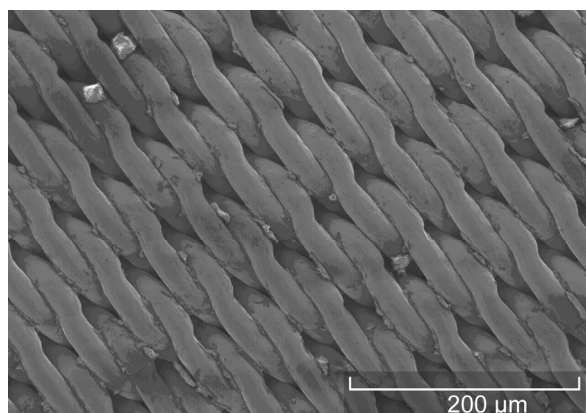Figure 9.—10 µ filter screen before cleaning.

Figure 10.—10 µ filter screen before cleaning.

Appendix B—LAD Screen Pore Diameter Analysis

Introduction

The purpose of this analysis is to examine if there is the screen geometry configuration can be utilized to predict the measured bubble points associated with these screens. The analysis is based on the physical dimensions of the openings or gaps through the screen and the fact that gas phase must constrict to a certain size in order to be able to enter the hole. Three types of holes or gaps are considered: (1) Projections into the top surface of the screen, (2) gaps between two adjacent shute wires at the warp wire, and (3) gaps among four adjacent shute wires.

Bubble Point Calculation

The bubble point is defined as the pressure difference necessary for a gas bubble to overcome the pressure difference imposed by surface tension forces in order for the bubble to enter/pass through an orifice. Mathematically,

$$\Delta P_{BP} = \frac{4 * \sigma}{D_P} \tag{4}$$

Generally, IPA is used as the fluid of choice to characterize screens by determining the pore size. For the 325 by 2300 mesh, bubble point testing with IPA yielded a $\Delta P_{BP} = 24.2$ in H_2O (6.02 KPa). The resulting pore diameter is 0.000567 in. (0.0144 mm).

Physical Characteristics of 325 by 2300 Screen

The diameter of the "shute" wires is 0.001 in. (0.0254 mm). The diameter of the "warp" wires is 0.0015 in. (0.0381 mm). The configuration of the Dutch Twill wiring is that the "shute" wires are raveled and grouped in combinations of four. Two of these wires are on the top of the screen and two are below. Alternating top and bottom shute wires and redirected towards the other side at alternating warp wires.

Image Analysis for Pore Diameter

A scanning electron microscope image of 325 by 2300 mesh was obtained and is shown in Figure 11. Assuming that the pores are triangular in nature and the projection on the top surface is consistent through the thickness of the screen material, a triangle with the following dimensions are obtained by applying the scaling factor on the SEM image.

Hydraulic Diameter

In order to calculate the "area" of the triangular hole, it is necessary to split the triangle into two triangles that are separated by a line that forms a right angle with the "base" or the side that is 0.00249 in. (0.0632 mm) long. Two equations are then defined using the Pythagorean theorem:

$$h^2 + b^2 = L_2^2$$
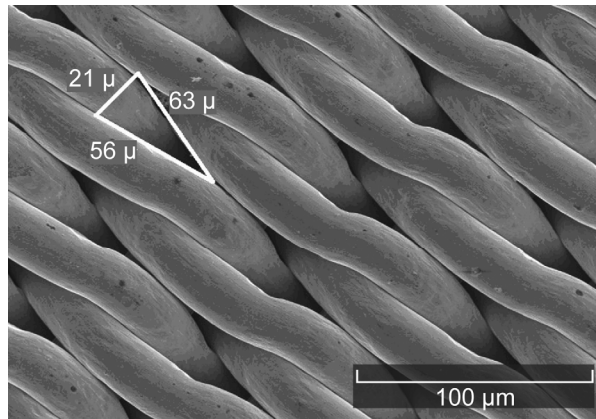
$$h^2 + (L_1 - b)^2 = L_3^2$$

Figure 11.—325 by 2300 screen showing dimensions
used for calculating hydraulic diameter.

TABLE 5.—325 BY 2300 MESH SCREEN DIMENSIONS
FOR CALCULATING HYDRAULIC DIAMETER

Side	Dimension
L_1	0.00249 in. (0.0632 mm)
L_2	0.00221 in. (0.0561 mm)
L_3	0.00083 in. (0.0211 mm)

Where h and b are the height of the triangle and b is the one of the lengths along the base side where the height line intersected the base. The area of the triangle was determined to be 8.99×10^{-7} in.^{2} (5.8×10^{-4} mm^2). Hydraulic diameter is defined as 4 times the cross-sectional area divided by the wetted perimeter or:

$$D_H = \frac{4 * A}{(L_1 + L_2 + L_3)}$$

For this screen, the resulting value is 0.00065 in. (0.0165 mm)

Inscribed Circle

The formula for the radius of a circle inscribe inscribed in triangle as

$$r = \sqrt{\frac{(s-a)(s-b)(s-c)}{s}}$$

Where $s = (a+b+c)/2$ and a, b, and c are lengths of the triangle legs. S is calculated to be 0.00276 in. (0.0678 mm) leading to an inscribed circle diameter of 0.00065 in. (0.0165 mm) as well.

Other Geometrical Configurations

Other geometries were analyzed as well including the gap between shute wires as they pass around a warp wire as shown in Figure 12, and between the four shute wires in the interval between warp wires as shown in Figure 13.
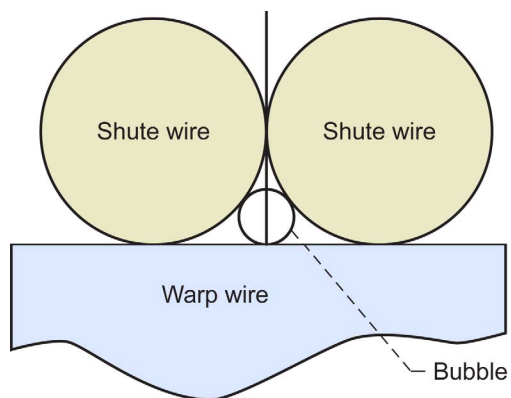
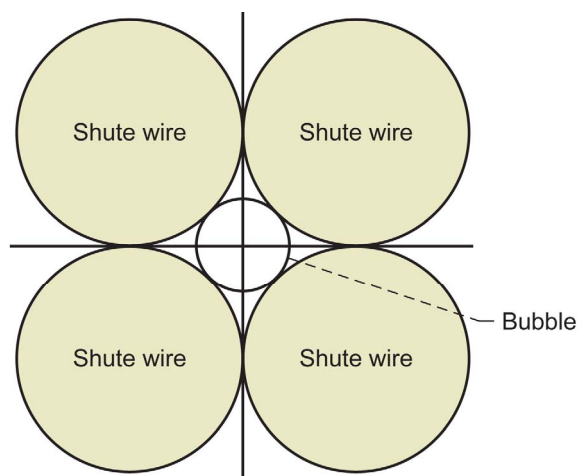Figure 12.—Gap between shute wires as they pass around warp wire.

Figure 13.—Gap between 4 shute wires in the interval between warp wires.

Three diameter "definitions" were analyzed for both cases: Inscribed circle, hydraulic diameter and "equivalent" diameter where the area available for flow was substituted into the definition for area of a circle. The "equivalent" diameter calculated for the case considered in Figure 13 yielded the correlation with historical data.

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14. ABSTRACT
Liquid acquisition devices (LADs) can be utilized within a propellant tank in space to deliver single-phase liquid to the engine in low gravity. One type of liquid acquisition device is a screened gallery whereby a fine mesh screen acts as a "bubble filter" and prevents the gas bubbles from passing through until a crucial pressure differential condition across the screen, called the bubble point, is reached. This paper presents data for LAD bubble point data in liquid methane (LCH_4) for stainless steel Dutch twill screens with mesh sizes of 325 by 2300.

These tests represent the first known nonproprietary effort to collect bubble point data for LCH_4.

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